

# REPORT DOCUMENTATION PAGE

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4. TITLE AND SUBTITLE Neuronal Micronets as Nodal Elements				5. FUNDING NUMBERS  G N00014-92-J-1923	
6. AUTHOR(S)  Thomas Huntington Brown					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Yale University, Grant and Contract Administration, 12 Prospect Place, New Haven, CT 06511-3516 Attn: Ms Sally Tremaine, Associate Director				8. PERFORMING ORGANIZATION REPORT NUMBER	
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11. SUPPLEMENTARY NOTES Attached letter from Thomas H. Brown dated Sept 16, 1996; attached Report of Inventions form.					
12a. DISTRIBUTION / AVAILABILITY STATEMENT No known restrictions on release of information				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) We have been working on developing a computationally efficient way to emulate neurons and to emulate circuits and networks of same. We made considerable progress in compressing "realistic" representations of neuronal computations into what we consider functionally equivalent input/output devices, which are now being incorporated into dynamic networks that learn associations and encode time. Our initial hypothesis about how to do this was rejected. Our new hypothesis offers great promise for scaling. This newer hypothesis resulted from examining simulations of "realistic" neurons and thinking about the scaling problem. The latter was funded by the ONR.					
14. SUBJECT TERMS Artificial neural networks; associative learning; Hebbian learning; competitive learning; dynamic processing elements.				15. NUMBER OF PAGES	
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# Yale University

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Campus address:  
2 Hillhouse Avenue.

September 16, 1995

Defense Technical Information Center  
Building 5, Cameron Station  
Alexandria, VA 22304-6145

Re: Final Technial Report on ONR grant N00014-92-1923

19960619 006

Dear Sirs/Mesdames:

*This is the final technical report on grant N00014-92-J-1923. This information has also been sent to Dr. Thomas McKenna, the Administrative Grants Officer, and the Director of the Naval Research Laboratory.*

The overarching goal of this grant "Neuronal Micronets as Nodal Elements" (N00014-92-J-1923) application was to determine the computational significance of the amount and type of information processing that actually occurs in the nervous system at the single-neuron level.

The basic thesis was that a neuron can be compared to a multi-layered artificial neural network (ANN). The question is, what kind of ANN best captures neuronal computations? This question raises several others: How do neurons differ from the processing elements (PEs) used in connectionistic studies? What do single neurons compute? We have been addressing the latter question through compartmental simulations of hippocampal neurons containing Hebbian synapses.

I used the term "micronet" to refer to the type of ANN that can capture neuronal computations<sup>1</sup>. I concluded that micronets are deep (many layers of PEs) but narrow (relatively few PEs per layer). To function like a neuron, the PEs must operate continuously and asynchronously. There is no clock. Time is its own representation. Connections within a micronet are assumed not to be modifiable, but connections among micronets can exhibit use-dependent modifications, which can be Hebbian. The PE activation function has a passive memory that decays rapidly and exponentially as a function of time.

I requested an AASERT for Sean Murphy, a neuroscience graduate student interested in this problem, but this application was not funded. Murphy went on however, working with another professor in my department, to begin building ANNs that could emulate the input-output functions of neurons, and this grew into part of his dissertation, which was just completed<sup>2</sup>. As I had anticipated, Murphy concluded that an appropriate neural network can indeed emulate a relatively realistic neuronal model in terms of gross input-output functions.

In working with one of my former students, we reached a similar conclusion, based on less formal or extensive analysis. The main difference, however, was that we concluded that, once learning is involved, the circumstance is quite different. And learning was an essential part of the problem we sought to understand. What follows summarizes some of the reasons for rejecting our initial basic thesis that a neuron can be compared to a multilayered ANN. The point is not that the enterprise cannot be done in principle, but that this approach is much too cumbersome relative to certain alternatives, if one is interested in learning.

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Part of the reason is that Hebbian learning depends on the electrotonic structure of the cells and this is not easy to capture in connectionist models<sup>3-9</sup>. Hebbian learning depends on the amplitude of the signal at the site of the synaptic input. This in turn means that voltage transfers to and from that site to and from every other synapse must be modeled. In addition, the effects of spiking in the soma must be represented in terms of voltage transfer back through the dendritic tree to the synapses.

These voltage transfers are in general not symmetrical—the attenuation from point  $i$  to point  $j$  is not the same as from  $j$  to  $i$  and they are frequency dependent<sup>10</sup>. Furthermore, nonlinear membrane responses, which our modeling suggested to be important<sup>11-13</sup>, particularly the backpropagation of action potentials into the dendrites<sup>5</sup>, are very difficult to incorporate in an ANN that includes Hebbian learning but have recently been suggested based on experimental data.

Why this insistence on Hebbian learning? Based on first principles, it has always been clear that Hebbian synapses were theoretically important<sup>4,13,14</sup> and we and others had previously shown them to exist in hippocampus. Now it seems that Hebbian synapses are extremely widespread. One sees such synapses in brain regions other than the hippocampus. One even sees such synapses in lower vertebrates. Most recently, it seems that they may even exist in invertebrates.

Thus we continued to explore electrotonic structure in order to understand better how it might interact with active membrane and Hebbian learning<sup>16-20</sup>. At the same time, we developed advanced methods to gain a better understanding of the diversity of cell types and their characteristic active membrane properties<sup>13,21</sup>.

My conclusion from this work was that it is computationally easier to use analog models or devices instead of trying to make an ANN emulate what such circuitry would do. If learning can be done off line, or if learning is not involved, then the original idea of representing a neuron as a micronet still makes sense<sup>2</sup>. But from what we now know about the neurophysiology, the nervous system is continuously self-organizing and exhibiting various forms of learning and that these will ultimately depend critically on the electrotonic structure and nonlinear dynamics. Therefore, I focused on the latter. We have gained deep insights into single neuron computations from this enterprise.

We have now begun to formalize the manner in which Hebbian self-organization depends on electrotonic structure<sup>10,22</sup>. The effect of nonlinear membrane probably will differ in different classes of cells and for different types of synaptic inputs. What we are learning is that there is no canonical neuron, even within highly circumscribed brain regions. The number of different types is large and we suspect that this means that brain-style computations require a correspondingly large number of elemental devices—in contrast to the conventional assumptions in ANNs.

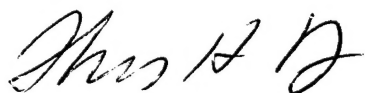
You will recall that this application was submitted in March of 1992, and I received notice that it would receive no further funding on August of 1993. At this time I requested a no-cost extension.

We are still publishing work from this period and the enterprise motivated us to collect experimental data that confirmed the conclusions based on the simulations mentioned above. Additional manuscripts are in preparation. I am currently working on what I think may be a fundamental new mechanism for how the nervous system encodes time using Hebbian synapses. I am also continuing to work on the design of a simple device that can, with small quantitative variations, learn and self-organize the way real neurons do. In contrast to Murphy's approach<sup>2</sup>, this elemental device would not be an ANN that emulates a particular neuron. Rather I am looking for an analog device that can capture the essence of our insights based on the above considerations. I hope to explore these ideas further through interactions with certain electrical engineers at Yale.

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Sincerely,

A handwritten signature in black ink, appearing to read 'Thomas H. Brown', written in a cursive style.

Thomas H. Brown, Ph. D  
Professor of Psychology  
Professor of Cellular and Molecular Physiology

# REPORT OF INVENTIONS AND SUBCONTRACTS

(Pursuant to "Patent Rights" Contract Clause) (See Instructions on Reverse Side.)

Public reporting burden for this collection of information is estimated to average 5 minutes per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0104-0187), Washington, DC 20503.

1. NAME OF CONTRACTOR/SUBCONTRACTOR Yale University		2. CONTRACT NUMBER N00014-92-J-1923		3. NAME OF GOVERNMENT PRIME CONTRACTOR		4. CONTRACT NUMBER	
b. ADDRESS (include ZIP Code) 12 Prospect Place New Haven, CT 06511		a. AWARD DATE (YYMMDD) 92/07/01		b. ADDRESS (include ZIP Code)		4. AWARD DATE (YYMMDD)	
c. TYPE OF REPORT (X one) a. INTERIM <input checked="" type="checkbox"/> b. FINAL		d. REPORTING PERIOD (YYMMDD) a. FROM 92/07/01 b. TO 95/06/30					

## SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR (If "None," so state)		6. ELECTION TO FILE PATENT APPLICATIONS		7. DISCLOSURE NO. PATENT APPLICATION SERIAL NO. OR PATENT NO.		8. CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER	
a. NAME(S) OF INVENTION(S) (Last, First, MI)	b. TITLE OF INVENTION(S)	c. ELECTION TO FILE PATENT APPLICATIONS		d. DISCLOSURE NO. PATENT APPLICATION SERIAL NO. OR PATENT NO.		e. CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER	
		(1) United States	(2) Foreign	(1) Yes	(2) No	(1) Yes	(2) No
NONE							

9. EMPLOYER OF INVENTION(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR		10. ELECTO FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED	
(a) Name of Employer (Last, First, MI)	(b) Title of Invention	(c) Foreign Countries of Patent Application	
(d) Name of Employer			
(e) Address of Employer (include ZIP Code)			

## SECTION II - SUBCONTRACTS (Containing a "Patent Rights" clause)

6. SUBCONTRACTS AWARDED BY CONTRACTOR/SUBCONTRACTOR (If "None," so state)		7. SUBCONTRACT DATES (YYMMDD)	
a. NAME OF SUBCONTRACTOR(S)	b. ADDRESS (include ZIP Code)	(1) Award	(2) Close
NONE			

## SECTION III - CERTIFICATION

1. CERTIFICATION OF REPORT BY CONTRACTOR/SUBCONTRACTOR		2. DATE SIGNED	
(Not required if Small Business or Non-Profit Organization) (X appropriate box)		10/24/95	
3. I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have been reported.			
4. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL (Last, First, MI) Polmar, Suzanne K.			
5. TITLE Director Grant and Contract Administration			

Form 882, OCT 89

Previous editions are obsolete.

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